XR Musical Keyboard: An Extended Reality Keyboard with an Arbitrary Number of Keys and Pitches

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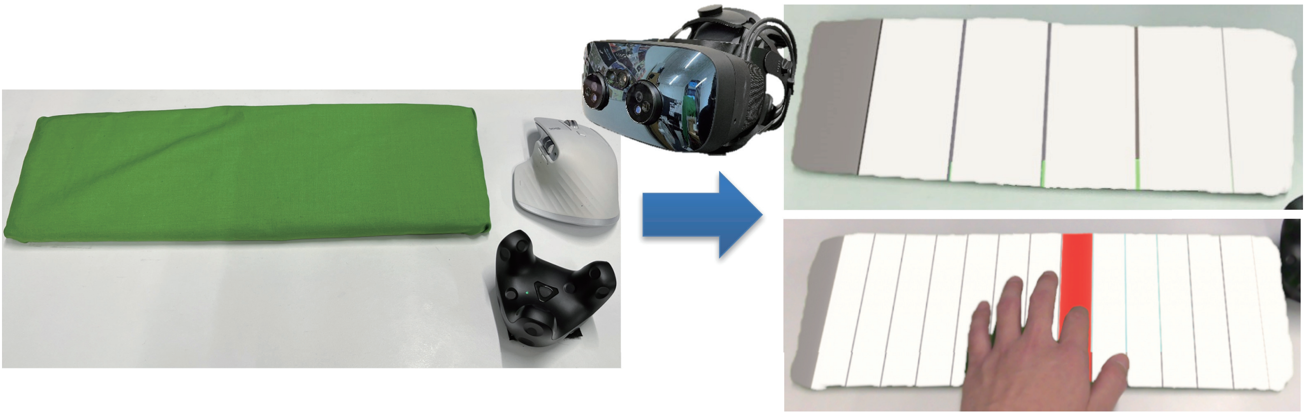

Figure 1: The experience of the XR musical keyboard, showing examples with 6 keys (top) and 15 keys (bottom) overlaid on a physical PC keyboard.

Abstract

We introduce the Extended Reality (XR) Musical Keyboard, a system allowing users to overlay a virtual keyboard onto a tabletop surface, such as a standard PC keyboard. This virtual keyboard is highly customizable: users can freely program the number of keys and their respective pitches. Modern software instruments offer advanced capabilities, including microtonal scales (pitches outside the standard 12-tone equal temperament). However, playing these instruments often remains challenging due to the lack of corresponding physical hardware. Our proposed solution addresses this gap by projecting a programmable virtual keyboard onto a tangible object within the XR space. This approach combines the software's flexibility with the tactile feedback of a physical surface, enhancing playability. Users can simplify the keyboard layout (e.g., fewer keys than a piano) or expand it beyond conventional limits to explore new expressive possibilities, particularly for microtonal music. We conducted a small pilot study (N=4) involving participants mostly inexperienced with keyboards to gather preliminary feedback on the interface's ease of use for performance.

Keywords

XRMI, XR, Microtones, Microtonal music

1 Introduction

Information technology continues to reshape musical interaction, offering novel tools like software instruments and Digital Audio Workstations (DAW) for expression. However, a gap often exists between flexible software capabilities and rigid hardware controllers. For example, software keyboards can be easily resized or reconfigured, while physical MIDI controllers remain fixed, limiting the expressive potential offered by software.

This limitation is particularly evident with microtonal music. While software instruments can readily simulate microtones (pitches falling between the standard 12 semitones), conventional hardware controllers like MIDI keyboards are typically designed for 12-tone equal temperament. This makes performing microtonal music or inputting it into DAW using standard hardware awkward and unintuitive. Hardware controllers designed specifically for microtones could significantly simplify microtonal music production. Furthermore, while software can generate any sound, the physical interaction with an instrument often sparks novel musical ideas, highlighting the need for hardware that mirrors software's adaptability.

Extended Reality (XR)—encompassing Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR)—offers a promising avenue to bridge this hardware-software divide. Research in Virtual Reality Musical Instruments (VRMI) explores replicating rare or physically impractical instruments and enabling novel performance modes [20]. XR allows virtual instruments to be customized in shape and size, mirroring software flexibility within an augmented physical environment. Recent work under the umbrella of Extended Reality Musical Instruments (XRMI) investigates new musical possibilities grounded in physical reality.

We propose an XR musical keyboard that leverages XR's strengths to combine software flexibility (customizable key numbers and pitches) with tangible interaction (overlaying the virtual keyboard onto a physical surface, such as a PC keyboard). This system aims to provide an accessible platform for exploring diverse musical scales, including microtones, by adapting to the user's skill level and preferences and overcoming the limitations of traditional hardware.

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2 Related Work

Several technological approaches have addressed aspects of microtonal music creation and flexible instrument control.

Microtonal Software and Hardware: Software tools facilitate the exploration of microtonality. Hirai developed an interface for designing custom scales and piano rolls [11]. Tools like Leimma[1] and Scala [15] support alternative tuning systems, contributing to a growing interest in de-Westernized musical practices. However, these often rely on standard MIDI controllers, creating a mismatch between software potential and hardware input. While some traditional instruments (e.g., violins, trombones) inherently support microtones, research has also focused on creating dedicated microtonal hardware. Examples include Bailey et al.'s microtonal clarinet [1] and Dabin et al.'s 3D-printed microtonal flute [3]. Digital fabrication enables customizable instrument designs [21, 22], but building physical instruments remains complex and costly. Crucially, physical instruments typically cannot change their tuning easily after construction.

Flexible Controllers and VR/AR/MR Instruments: Alternative hardware controllers like ROLI's Seaboard[2] (continuous key surface) and Joué Play[3] (modular pads) offer increased flexibility but are still bound by their physical form factors. VR offers purely virtual environments for music creation, like KORG Gadget VR[4], which allows users to build virtual studios. However, the lack of tangible interaction can hinder performance feel.

VRMI aim to bridge this gap [20]. Researchers have recreated rare instruments virtually [8] and developed VR pianos with haptic feedback, like AirPiano [12]. Others have explored alternative keyboard layouts optimized for VR [2]. A key challenge in VR is hand tracking and representation; virtual hands often lack the fidelity needed for precise instrument playing. Some designs circumvent this by creating VRMIs independent of traditional instrument forms [10].

AR and MR offer alternatives by overlaying virtual elements onto the real world, allowing users to see and use their actual hands. Santini's Augmented Piano [18] overlays visuals onto a real piano, enhancing it with new sounds and effects while retaining natural hand interaction, potentially offering easier performance than pure VRMI. Desnoyers-Stewart et al. created an MR MIDI keyboard [4, 5], though MR hardware dependency can limit accessibility.

Our work builds upon these areas by using pass-through XR to create a tangible, yet fully customizable keyboard interface, focusing on the potential for arbitrary key layouts and microtonal exploration.

3 The XR Musical Keyboard System

We developed an XR musical keyboard system where a software-defined virtual instrument is overlaid onto a tangible surface using a pass-through Head-Mounted Display (HMD). For this implementation, we used a standard PC keyboard as the tangible surface, but any object providing distinct press locations could potentially be used. The core idea is to align the 3D virtual keyboard with the physical object (e.g., PC keyboard). This allows users to see their own hands interacting with the virtual keys while receiving tactile feedback from pressing the underlying physical keys. Users see virtual keys, press them with their actual hands, and hear the assigned sounds, mimicking the interaction with a physical keyboard. This approach merges the flexibility of software instrument design (custom key counts and pitches) with a tangible playing experience, offering an accessible platform particularly suited for exploring microtonal music.

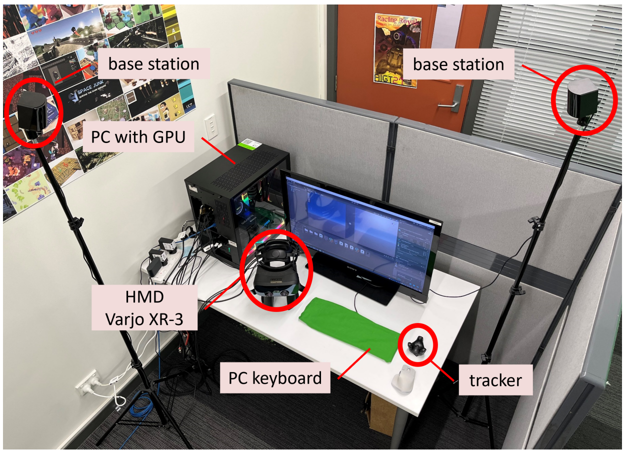

Figure 2: Components of the XR musical keyboard setup.

3.1 System Overview

Figure 1 illustrates the user experience. In our setup, the physical PC keyboard is covered with green cloth. This enables chroma-key compositing via the HMD's pass-through cameras: the green area is replaced by the virtual keyboard, while the rest of the real-world desk and the user's hands remain visible. When playing, the user's hands naturally occlude parts of the green cloth, creating a visually integrated experience where hands appear to directly interact with the virtual keys (Fig. 1). A tracker (e.g., Vive Tracker) placed near the covered keyboard allows the system to precisely align the virtual instrument model with the physical keyboard in the XR space.

The virtual instrument itself is a keyboard whose key count, arrangement, and pitch assignments are customizable. Figure 1 shows examples: a simplified 6-key layout (perhaps one octave using 5 keys plus the octave repeat) and a more complex 15-key layout (potentially representing a 14-tone equal temperament octave). This flexibility allows tailoring the keyboard for simplicity or enhanced expressiveness.

The hardware components are shown in Figure 2. We used a Varjo XR-3 video pass-through HMD, known for its high resolution and wide field of view, running on a high-specification PC (Intel i9-10900KF, 32GB RAM, Nvidia RTX3080). The prototype was developed in Unity (v2021.3.3f1).

While optical pass-through HMDs exist, current models often have limitations like a narrower field of view, which can hinder the sense of immersion. Video pass-through was chosen for this implementation, though future HMD advancements may allow realization on various platforms.

In addition to the HMD and PC, the system uses a Vive Tracker 3.0 for positioning the virtual keyboard relative to the physical one, and two SteamVR Base Stations 2.0 for tracking the HMD and tracker. A standard PC keyboard covered with green cloth serves as the tangible interaction surface. A mouse can optionally be used for control functions during performance.

The PC keyboard, covered by the green cloth (Figure 3), remains functional; its keys can still be pressed through the cloth.

[1] https://isartum.net/leimma
[2] https://roli.com/products/seaboard/rise2
[3] https://jouemusic.us/
[4] https://www.korg.com/us/products/software/korg_gadget_vr/

Figure 3: PC keyboard covered with green cloth for chroma-keying, remaining pressable.

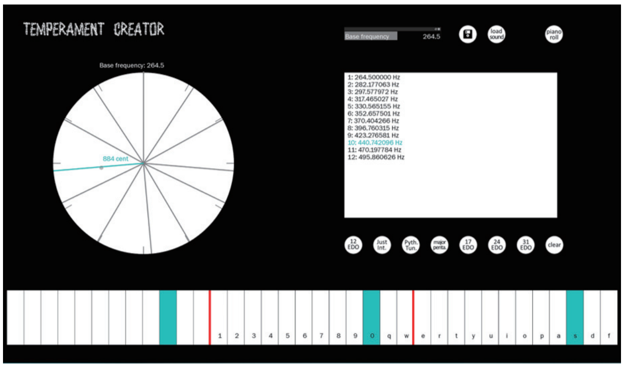

Figure 4: Temperament design interface (adapted from Hirai, 2022 [11]) used for changing the number and pitch of keys.

While green is commonly used for chroma-keying, any distinct color that can be cleanly keyed out could work. Covering with cloth was chosen for simplicity and compositing quality in this prototype, but other readily available items could potentially substitute.

3.2 Customizing Keys and Pitches

The number of virtual keys per octave and their specific pitches are configured using an interface based on Hirai's scale design tool [11] (Figure 4). This interface allows users to add or remove keys within an octave and adjust the pitch of each key finely (in cents), starting from standard templates or creating scales from scratch.

Once a scale is designed, the system exports the key count and frequency data as a text "tuning file". By default, it saves pitch information for one octave plus the first note of the next octave (e.g., 13 notes for 12-tone equal temperament, C4 to C5).

These tuning files can be loaded dynamically during an XR session. While wearing the HMD, the user can use the mouse to select and load a different tuning file, instantly changing the virtual keyboard's layout and pitches. This enables unique performance possibilities, like switching between different temperaments (e.g., 12-EDO and 17-EDO) mid-piece, analogous to modulation but changing the entire scale structure. Similar to standard MIDI controllers, the system also includes octave shift functionality (implemented via mouse clicks in the current prototype).

A practical limitation is that if the number of virtual keys becomes very large, individual virtual keys may become smaller than the underlying physical keys. This can lead to misalignment issues that require careful consideration of the maximum practical key density for a given physical base.

Table 1: Each participant's experience playing keyboard instruments and ability to read sheet music.

Evaluator	Keyboard playing experience	Ability to read sheet music
1	Has tried but cannot play	Cannot read
2	Can play to some extent	Can read
3	No experience at all	Cannot read
4	Has tried but cannot play	Can read a little

Figure 5: Interface used for comparison (control condition), simulating a standard 12-key piano layout in XR.

Figure 6: An example of numbered musical notation used in the pilot study.

4 Pilot Study and Preliminary Feedback

To gather initial user feedback on the proposed system, we conducted a small pilot study focused particularly on the ease of performance with customizable key layouts. Given the limited sample size (N=4), this study should be considered as a preliminary investigation rather than a definitive evaluation.

4.1 Method

The study focused on comparing the ease of playing simple melodies using two different XR musical keyboard layouts overlaid on a PC keyboard:

- Simplified Layout (Experimental): 6 keys per octave (corresponding to C, D, E, F, G, A white keys).
- Standard Layout (Control): 12 keys per octave (standard piano layout with white and black keys, Fig. 5).

Four participants (male and female, aged in their twenties, mostly novices with keyboards - see Table 1) took part. We prepared four short, well-known melodies playable using only the first six notes (C to A). Participants played each melody on both the 6-key and 12-key interfaces. They first listened to the melody, then attempted to play it using simplified numbered sheet music (Fig. 6) corresponding to numbers displayed above the virtual keys (Fig. 7). The order of the interfaces was alternated between melodies to mitigate learning effects.

After playing each melody on both interfaces, the participants answered brief questions that compared the ease of playing. After all trials, they provided overall qualitative feedback. The session took approximately 10 minutes per participant.

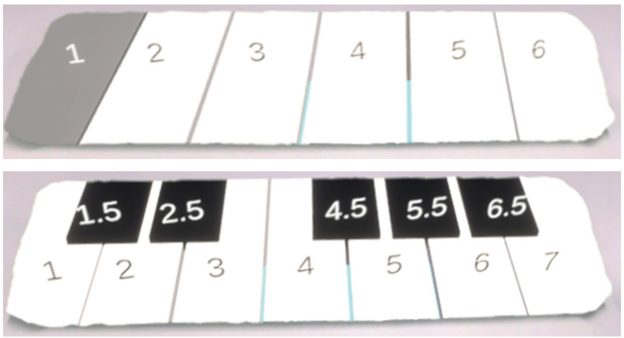

Figure 7: Visualization of keyboard numbers for musical score compatibility.

4.2 Interfaces Compared

Both the 6-key (simplified) and 12-key (standard) interfaces were presented within the same XR system, overlaid on the PC keyboard. The only difference was the virtual keyboard layout displayed and the mapping of physical keys to notes. The melodies used only the notes available in both layouts (effectively, the white keys C-A). During the evaluation, numbers corresponding to the musical score (which could be toggled on/off) were displayed above the virtual keys as shown in Fig. 7.

4.3 Musical Material and Notation

Four simple, well-known melodies were used:

(1) Mary Had a Little Lamb (first 8 measures)
(2) Twinkle, Twinkle, Little Star (first 12 measures)
(3) Jingle Bells (16 measures)
(4) London Bridge is Falling Down (first 8 measures)

To accommodate participants with varying music reading abilities, melodies were presented using numbers (Fig. 6) corresponding to numbers displayed above each virtual key (Fig. 7). Numbers floated above the keys. For the 12-key interface, numbers were assigned sequentially to white keys, with decimal numbers for the unused black keys to maintain spatial correspondence.

The numbered sheet music was provided both on paper (placed near the keyboard) and on a monitor; participants could choose their preferred reference. Participants played by matching the numbers on the score to the numbers on the virtual keys. They were allowed to restart if they made a mistake, continuing to the next trial once a piece was played through.

4.4 Questionnaire Items

After each melody trial (playing on both 6-key and 12-key interfaces), participants answered:

(1) Familiarity with the melody (Yes/No).
(2) Perceived melody complexity (5-point scale: 1=Easy to 5=Difficult).
(3) Comparative ease of playing (5-point scale: 1=12-key much easier, 3=Equal, 5=6-key much easier).
(4) Overall impressions/comments (Free-form, after all trials).

5 Pilot Study Results and Observations

This section presents the results from the small pilot study (N=4). Table 2 shows the average scores for the questionnaire items after each melody. A score closer to 1 on "Ease of Play" indicates the 12-key interface was perceived as easier, while a score closer to 5 indicates the 6-key interface was easier.

Table 2: Pilot Study Results (Average Scores, N=4)

song no.	Evaluation Item: Familiar with this melody?	Is this melody complex?	Which was easier to play?
1	Yes, n=4	1.25	2.75
2	Yes, n=4	1.75	4.00
3	Yes, n=4	1.75	3.50
4	Yes, n=4	1.75	4.50
Ave	Yes, n=4	1.63	3.69

All participants were familiar with all melodies. The melodies were generally perceived as simple (average complexity score 1.63). Regarding ease of play, the overall average score was 3.69, suggesting a slight trend favoring the 6-key interface among this small group. However, preference varied by song (e.g., Song 1 average was 2.75, favoring the 12-key) and individual participant responses also showed variability (not shown in the averaged table).

Qualitative feedback collected after all trials included comments such as:

- Some found the black keys on the 12-key layout helpful for orientation, making the 6-key layout feel harder for certain songs.
- Conversely, some found the 12-key layout slightly harder to play due to narrower key spacing caused by the black keys.
- The 6-key layout was described as easy to recognize and press by some.
- The wider spacing of the 6-key layout felt different from a traditional piano.
- Both layouts were generally found to be intuitive.
- A perceived slight misalignment between the virtual keys and the physical PC keys was mentioned.
- The tactile feedback from the PC keyboard felt different/strange compared to a real piano.
- One participant commented on the potential for beginners to learn piano with this system.

Overall, initial feedback was cautiously positive, but highlighted potential areas for improvement, particularly the virtual-physical key alignment.

Pilot Study Interpretation: This preliminary study with only four participants suggests that interface preference (simplified 6-key vs. standard 12-key) might depend on the specific task (melody) and individual user factors (e.g., familiarity with piano layout). This hints that user customization of the keyboard layout could be beneficial. Even for novices, familiarity with the standard piano layout might provide orientation cues (black keys), while fewer keys might offer cognitive simplicity for others.

The 6-key layout used was only marginally different from the white keys of the 12-key layout within the tested note range (C-A). Future studies should explore more distinct key layouts (e.g., significantly fewer keys, or microtonal layouts with more keys) to better understand the impact of customization.

This pilot study focused solely on ease of playing simple melodies for novices, comparing only different key configurations. It did not evaluate the system's potential for enhanced expressiveness (e.g., with microtonal scales) or other usability aspects. More comprehensive evaluations with larger, diverse

Figure 8: Example concept of arranging an 88-key XR musical keyboard on a standard tabletop.

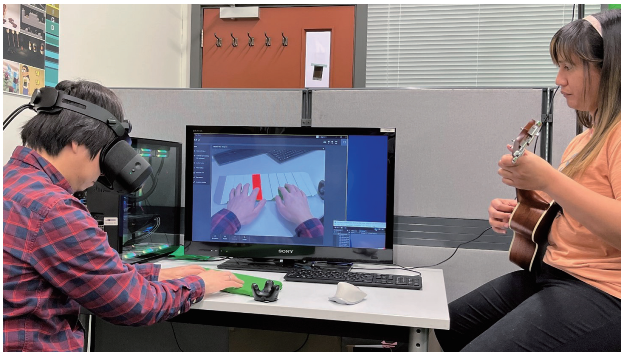

Figure 9: Concept illustration: Session between an XR musical keyboard user and a musician playing a physical instrument (ukulele).

participant groups are needed. For future work, we plan to conduct more comprehensive evaluations focusing on expressive capabilities and microtonal performance, incorporating objective performance metrics such as error rates and timing accuracy.

6 Discussion: Potential Applications

Beyond the preliminary findings, the proposed XR keyboard concept opens up several potential application areas.

Space-Efficient Large Keyboards: While standard pianos have 88 keys, common MIDI controllers are smaller (e.g., 25, 49 keys) partly due to desk space constraints. Our system could potentially map a full 88-key layout (or even larger custom layouts) onto a compact physical surface like one or more PC keyboards (conceptualized in Fig. 8), arranged creatively (e.g., multi-row). While precise mapping requires further development (see Sec. 7), the concept allows large virtual instruments in limited physical spaces.

Mixed Reality Ensembles: Although the virtual keyboard requires an HMD, the sound produced can be heard by anyone nearby. This facilitates ensemble playing between an XR keyboardist and musicians playing traditional physical instruments (conceptualized in Fig. 9). Furthermore, XR platforms are well-suited for remote collaboration. Integrating our system with remote session technologies [19] could enable mixed ensembles involving local physical musicians, local XR musicians, and remote collaborators (virtual or real). While this paper focuses on the keyboard, the underlying principles could potentially extend

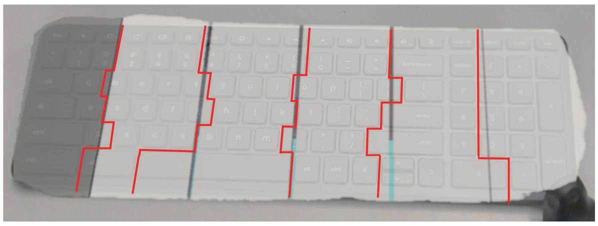

Figure 10: Illustration of potential misalignment: pressing near a virtual key boundary might activate the wrong underlying physical key.

to other virtual instrument forms within such collaborative XR environments.

7 Conclusion and Future Work

We introduced an XR music keyboard concept that overlays a customizable virtual keyboard (arbitrary key count and pitches) onto a tangible surface (e.g., a PC keyboard) using pass-through XR. This approach aims to combine the flexibility of software instruments with the tactile feedback of physical interaction. A small pilot study (N=4) with novice users provided preliminary feedback, suggesting a slight preference for a simplified 6-key layout over a standard 12-key layout for playing simple melodies, although results varied and highlighted the potential value of user customization. The pilot study focused narrowly on ease of play; further research is needed to evaluate expressiveness (especially with microtonal scales), usability, and overall performance capabilities.

A key limitation identified in the current prototype is the potential misalignment between virtual keys and the underlying physical keys, especially at key boundaries or with high key densities (as illustrated in Fig. 10). Pressing near a virtual boundary might trigger an adjacent physical key, leading to unintended notes.

Future work will focus on addressing this alignment challenge. While hand-tracking integrated into HMDs could potentially determine intended key presses more accurately, current technology often lacks the precision and speed required for complex musical performance [6, 7]. Alternative solutions include using input surfaces with higher spatial resolution (e.g., capacitive touchpads, pressure-sensitive surfaces) instead of discrete PC keys, or potentially combining the PC keyboard with improved hand-tracking algorithms to infer intent based on finger position relative to virtual key boundaries.

Our current version of the XR musical keyboard focuses solely on key configurations. The integration of hand tracking and other XR-specific interactions, such as voice and gesture input, is expected to enable richer musical expression beyond simple key-to-note mapping. Future work will explore these possibilities, including Theremin-inspired gesture controls that enable expressive features such as portamento and pitch-shift effects, along with voice-based timbre control. While the current interface provides only basic functionality, it demonstrates significant potential for expansion. We will further explore the possibility of enabling expressions that simply cannot be played without XR technology.

Beyond the keyboard interface, the application of customizable XR overlays could be explored for other instrument types (e.g., virtual strings, winds, percussion) and novel VRMI designs

[14]. In addition to expressive potential, customizable keyboard dimensions (size and inter-key spacing) could benefit educational applications, particularly in piano pedagogy. This represents a compelling research direction worthy of further investigation. Integrating our system with existing research in XR for music education [9, 13, 16, 17, 23] and remote collaboration [19] presents exciting possibilities for expanding musical practice and performance through XR platforms.

8 Ethical Standards

This research adheres with the NIME ethical standards. Participants in the pilot study were informed about the procedure and gave their consent prior to participation. All collected data was anonymized; no personally identifiable information was retained. Participants consented to the use of anonymized data for research purposes.

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